Decadal Variation of the Southwest U.S. Summer Monsoon Circulation and Rainfall in a Regional Model

Q. Steven Hu
University of Nebraska - Lincoln, qhu2@unl.edu

Yongjun Zheng
University of Nebraska - Lincoln, songfeng@uark.edu

Decadal Variation of the Southwest U.S. Summer Monsoon Circulation and Rainfall in a Regional Model

QI HU AND SONG FENG

Climate and Bio-atmospheric Sciences Group, School of Natural Resources, and Department of Geosciences, University of Nebraska at Lincoln, Lincoln, Nebraska

(Manuscript received 25 May 2006, in final form 4 January 2007)

ABSTRACT

Previous studies have identified several major causes for summer rainfall variations over the southwest United States, for example, land memory (i.e., relationships between antecedent winter season precipitation and snow cover anomalies and subsequent summer rainfall anomalies over the southwest United States; these anomalies are likely most important in the northwest United States, although antecedent anomalies in the southwest United States also may be important in determining summer rainfall variations) and sea surface temperature (SST) anomalies in the North Pacific. Atmospheric responses to these "boundary forces" interact with moisture flows from the Gulf of Mexico and from the Gulf of California to influence the rainfall in the Southwest. The land memory and the SST effects were further found to be "naturally separated," in the sense that they each played a dominant role influencing the monsoon rainfall variation during different periods of the last century. This separation was also manifested by different dominant low-level moisture transport anomalies in those periods. Several new questions have arisen from these findings: How have the land memory and the SST effects been "separated," so as to affect the monsoon rainfall variations during different periods, or "regimes"? And, what are the corresponding changes of low-level flows, and hence moisture transports into the southwest United States that help achieve the land memory or the SST effects on the rainfall variations during these different regimes? These questions, and related issues, are addressed using a numerical model of regional climate. The model was used to simulate 14 individual warm seasons (April–October) in each of the postulated regimes. Analyses of the simulation results showed systematic and significant changes in atmospheric circulation anomalies between the two regimes. In the early regime (1961–90), when the land memory effect was strong, the average geopotential height was lower and storm activity was more intense over the central and western United States than in the more recent regime (from 1990 on), indicating reduced eddy energy and momentum exchanges between high and low latitudes in the western United States. The effects of these changes on the monsoon rainfall were achieved by very different low-level flow and moisture transport anomalies. In the earlier regime, low-level flow and moisture transport anomalies in the southwest United States were primarily due to easterlies and southeasterlies into the Southwest for its wet monsoon conditions, with reversed anomalies for dry conditions. In the recent regime, these anomalies changed, with primarily southerlies and southwesterlies from the Gulf of California into the Southwest during its wet monsoon conditions, and reversed flow anomalies for dry conditions. These changes indicate that different physical processes, including those responsible for the planetary-scale atmospheric circulation, led to monsoon rainfall variations during each of these regimes.

1. Introduction

Rainfall during the 3-month period July–September accounts for nearly 50% of the annual precipitation in the semiarid southwest United States. This relatively wet period, often referred to as the southwest U.S. monsoon season, is of considerable interest and importance, especially its interannual variation. Several causes potentially influencing the monsoonal rainfall variation have been identified in recent years, including 1) a "land memory" effect, which describes anomalous land surface fluxes of water and energy in the warm season resulting from antecedent winter precipitation and snow cover anomalies over both the northwest and southwest United States, and influences of those anomalies on warm season rainfall in the southwest

Corresponding author address: Dr. Qi Hu, University of Nebraska at Lincoln, 707 Hardin Hall, Lincoln, NE 68583-0987.
E-mail: qhu2@unl.edu

DOI: 10.1175/JCLI4270.1

United States (Gutzler and Preston 1997; Higgins and Shi 2000; Hu and Feng 2002, 2004a); 2) North Pacific sea surface temperature (SST) anomaly effect, which describes the influence of the SST anomaly on variations of large-scale atmospheric circulation and their subsequent effects on monsoon rainfall in the southwest United States (Carleton et al. 1990; Castro et al. 2001; Hu and Feng 2004b); and 3) effects of low-level southerly jets, which describe relative influences of moisture transports from the Gulf of California and from the Gulf of Mexico in the development of the southwest U.S. monsoon rainfall (Douglas et al. 1993; Douglas 1995; Stensrud et al. 1997; Adams and Comrie 1997; Berbery 2001; Anderson et al. 2002; Mo and Juang 2003).

We notice that the former two "causes" may be considered as the "boundary forcing" and the low-level jets are "internal processes" of the atmosphere. At this point, it remains unclear if the variations of the jets and their moisture transport anomalies may have resulted from variations of the land memory or the North Pacific SST anomalies, or if their influences on the monsoon rainfall may be a part of a larger-scale variation of the atmospheric circulation. It is a goal of this study to address these questions.

In any given year, regional atmospheric responses to the land memory and/or the North Pacific SST anomalies would interact and also would interact with the low-level jets to affect the southwest U.S. monsoon rainfall. Such interactions and resulting effects on the rainfall can vary. For instance, the land memory could play a dominant role in affecting rainfall in the monsoon period; the land memory effect could interact with a low-level jet and largely determine the amount and distribution of the monsoon rainfall; and furthermore, land memory and the SST anomalies could influence the regional circulation and yield complex effects on the rainfall. This perplexity of the processes influencing the rainfall in the monsoon period has challenged our understanding of the monsoon rainfall development and its predictability in the southwest United States (Ropelewski et al. 2005).

Although the effects of the land memory and the North Pacific SST anomaly and the low-level jets and related moisture transports could interact in various ways and affect the monsoon rainfall differently from year to year, some persistent patterns of such interactions in the last 100 yr have been identified (Gutzler 2000; Hu and Feng 2002, 2004b). For example, Hu and Feng (2002, 2004b) showed that the land memory effect had an especially strong influence on monsoon rainfall and its interannual variations in the two time periods from approximately 1921–30 and 1961–90. When the influence of the land memory effect weakened in the years before 1920 (data were available 1900–20), during 1931–60, and in the recent years after 1990, North Pacific SST anomalies began strongly influencing the monsoon rainfall. These observations suggest a possible separation, at multidecadal scales, between the effects of land memory and North Pacific SST anomaly.

This apparent natural separation of the two effects alleviates to some extent the complexity of the sources influencing the monsoon rainfall variation in the southwest United States. Further, it suggests that different circulation regimes may have persisted in those different periods so the atmospheric response to the land memory or SST anomaly could have been selectively signified to affect the regional circulation and rainfall anomalies in the Southwest. In other words, different regional circulations in the different regimes may have selectively strengthened different low-level jets (LLJs) (from the Gulf of California or from the Gulf of Mexico). These jets are the primary means of moisture transport into the southwest United States during the monsoon season (e.g., Rasmusson 1967; Hales 1972). Although both jets transport moisture into the southwest United States they go through different routes and are due to differing processes (Schmitz and Mullen 1996). As summarized in Mo and Juang (2003), the southeasterly LLJ from the Gulf of Mexico "supplies moisture to eastern Mexico and New Mexico from upper levels above 700-hPa, [while] the significant moisture source contributing to rainfall over northern Mexico and the Southwest including Arizona and New Mexico (AZNM) comes from the Gulf of California and the eastern Pacific." Thus, depending on which jet plays a major role in transporting moisture to the Southwest, there will be different spatial patterns and amounts of rainfall in the monsoon season.

In a regime, for example, the one when the land memory effect was strong, the circulation in the Southwest could have interacted/engaged with one of the jets and enhanced its moisture transport to the Southwest. Interactions of this enhanced low-level moisture flow with the regional circulation affected the monsoon rainfall. In the other regime, for example, when the North Pacific SST anomaly showed strong teleconnection with rainfall in the Southwest, the other jet could have been enhanced and strongly affected the monsoon rainfall variation. This hypothesis—that is, different circulation regimes existed in different periods and enhanced the land memory or the SST anomaly effect and a different low-level jet to influence the monsoon rainfall in the Southwest—will be examined in this study using numerical methods for the recent two regimes identified in Hu and Feng (2002). Results from evaluation of this

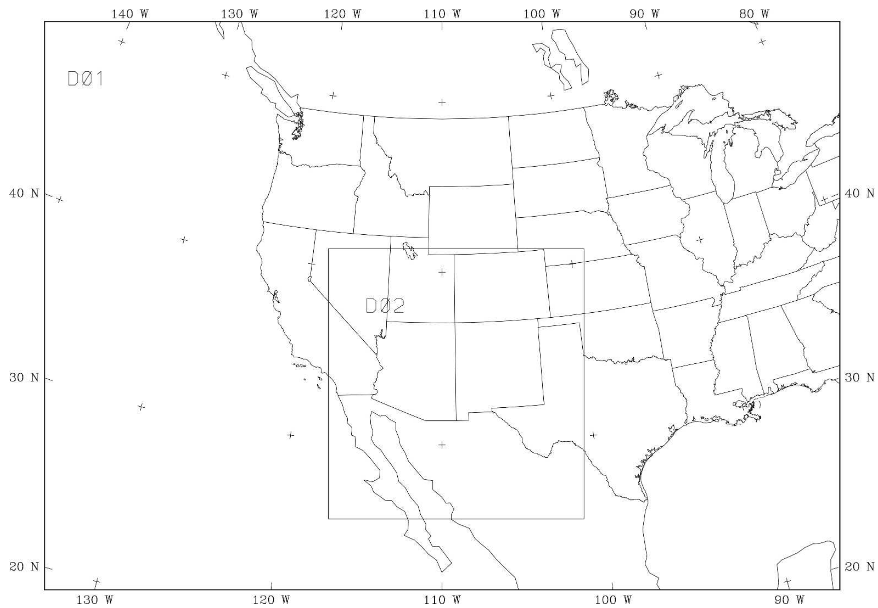

FIG. 1. Model domains: D01 shows the coarse domain of 90 km × 90 km resolution, and D02 shows the inner domain of higher resolution at 30 km × 30 km resolution.

hypothesis also will shed light on answers to the questions raised earlier.

The numerical model is described in the next section, followed by a description of the two sets of model simulations of seven individual years taken from the 1961–90 and 1990–present regimes. Results are shown in section 3. Further discussions of the results and major conclusions from this study are presented in sections 4 and 5, respectively.

2. Model and simulations

a. Model

The fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5; Grell et al. 1994) was used. The model's ability to describe the summer monsoon rainfall in the southwest United States was examined in Gochis et al. (2003) and Gutzler et al. (2005). The former focused on the sensitivity of MM5 to various convective parameterizations in simulating southwest U.S. summer rainfall in 1999, and the latter compared MM5 with a group of other models for strengths and weaknesses in describing the diurnal cycle, circulation features, and rainfall in the southwest United States during the warm season of 1990. These previous studies have indicated that MM5 can describe reasonably well the warm season rainfall when using the Kain–Fritsch convection parameterization (Kain and Fritsch 1990). In the case of 1990 (Gutzler et al. 2005), the model-simulated summer diurnal and seasonal cycles of rainfall compared well with that observed, albeit the model produced considerably more precipitation than observed. While showing some limitations of the model, these previous studies suggest that MM5 is able to describe adequately qualitative patterns and variability of warm season rainfall and variation in the southwest United States.

In this study the MM5 was used with the Kain–Fritsch convection parameterization, along with the simple ice module and cloud radiation of Grell et al. (1994) for explicit cloud microphysics and atmospheric radiation, the Noah land surface scheme (Chen et al. 1996) for land surface processes, and the Medium-Range Forecast Model (Hong and Pan 1996) for the planetary boundary layer. Nested domains were used with a fine-resolution domain of 30 km × 30 km centered in the Arizona–New Mexico area (Fig. 1) to resolve mesoscale details of the summer rainfall in the Southwest. A coarser-resolution domain of 90 km × 90 km was used to cover a broader region encompassing portions of the United States and the eastern North Pacific Ocean (Fig. 1). Lateral forcings at the outer boundary of the domain were derived from the National Centers for Environmental Prediction (NCEP)–NCAR reanalysis fields at a temporal resolution of 6 h daily (Kalnay et al. 1996), describing the planetary-scale circulation effects on atmospheric processes in the simulation region. The SST in the model's ocean grid points was assigned using the weekly dataset of Reynolds and Smith (1994) and linearly interpolated to 6-hourly values.

b. *Simulations*

The model was integrated from 1 April through 31 October for the years 1982–88 (of the regime encompassing 1961–90) and for the years 1995–2001 (of the recent regime from 1990 on). The land memory effect on monsoon rainfall in the Southwest was strong in 1961–90 but diminished after 1990, when the teleconnection of the SST anomaly on the monsoon rainfall increased (Hu and Feng 2004b). Composite differences between these simulations should demonstrate changes in large-scale circulations associated with the separation of the land memory and the SST anomaly effects, and associated changes of the regional circulation in the Southwest. They should also reveal different roles of the low-level jets and associated moisture transport in development of the monsoon rainfall in the Southwest during the different regimes.

c. *Observations used for comparisons with model results*

Gridded daily precipitation and air temperature derived from observations were used to compare with the model results. The precipitation data are from Higgins et al. (2000) and have a spatial resolution of $1.0° \times 1.0°$ covering the United States and Mexico. The monthly maximum and minimum surface air temperatures were from New et al. (2000) and have a spatial resolution of $0.5° \times 0.5°$ covering the global land area. These datasets are based solely on measurements of land stations.

3. Results

a. *General features of the simulated and observed climate of the southwest United States*

Figure 2 shows the simulated and observed averaged monthly precipitation for July and August, and averaged July–September total rainfall, in domain 2 of Fig. 1. The model averages were made from the two 7-yr simulations, 1982–88 and 1995–2001, and the observation averages were for the same years. In Fig. 2, both the magnitude and spatial distributions of the simulated average monthly rainfall and the average 3-month [July–September (JAS)] rainfall resemble the observations. The primary feature in the warm season rainfall distribution is a maximum in rainfall over the Sierra Madre Occidental in Mexico. This rainband extended into Arizona and New Mexico, and further stretched northeastward to the U.S. central Great Plains. The paucity of precipitation in Nevada and southern California also was simulated, consistent with the observations. Time variations of the 14-yr averaged daily rainfall in the warm season in the southwest United States (an area in 32.0°–36.0°N, 107.5°–112.5°W) are shown in Fig. 3. The simulated rainfall captured the observed onset of the monsoon rainfall in early July. The simulation also depicted the monsoonal precipitation distribution, with low precipitation before the onset and high precipitation from the onset through the end of the monsoon in September.

The simulated and observed surface temperatures are shown in Fig. 4, in a similar format as Fig. 2. The simulated temperature distribution and variation compared well with the observations. For example, cooler temperatures were found over the mountainous regions of the U.S. Rockies, as well as the Sierra Madre Occidental in Mexico, with warmer temperatures in the Sonoran Desert areas of southwest Arizona. Seasonally cooler temperatures in most of the southwest United States in September occurred in both the simulation and the observation (not shown).

In addition to the surface temperature and rainfall, the upper-atmosphere circulation also showed coherent features between the simulations and observations. For instance, in Fig. 5 we compare the simulated and the observed 500-hPa geopotential height for July–September. The comparisons were made both for the 14-yr average (Figs. 5a,b) and separately for the two regimes (Figs. 5c–f). These results show that the simulated and the observed circulations possess the same spatial distribution in both the 14-yr average and averages of the two regimes. A minor difference is seen in the magnitude of the geopotential: the simulated is about 20 $m^2\ s^{-2}$ lower than the observed. This is also true for the 14-yr average shown in Figs. 5a,b, though the difference is smaller. This lower geopotential in the simulation reflects a minor cold bias in the model with reasons yet to be identified.

b. *Changes in circulation features between the regimes*

A comparison of the averaged July–September 500-hPa geopotential height between 1982–88 and 1995–2001 (Figs. 5c–f) indicates that the high pressure system centered over Texas and New Mexico intensified during the recent regime, 1995–2001. This increase was strongly shown by the higher ridge over the north-central and western United States, depicted in Fig. 6 by differences of 500-hPa geopotential height between the two regimes. The observed geopotential (Fig. 6b) also was higher in the central and western United States in

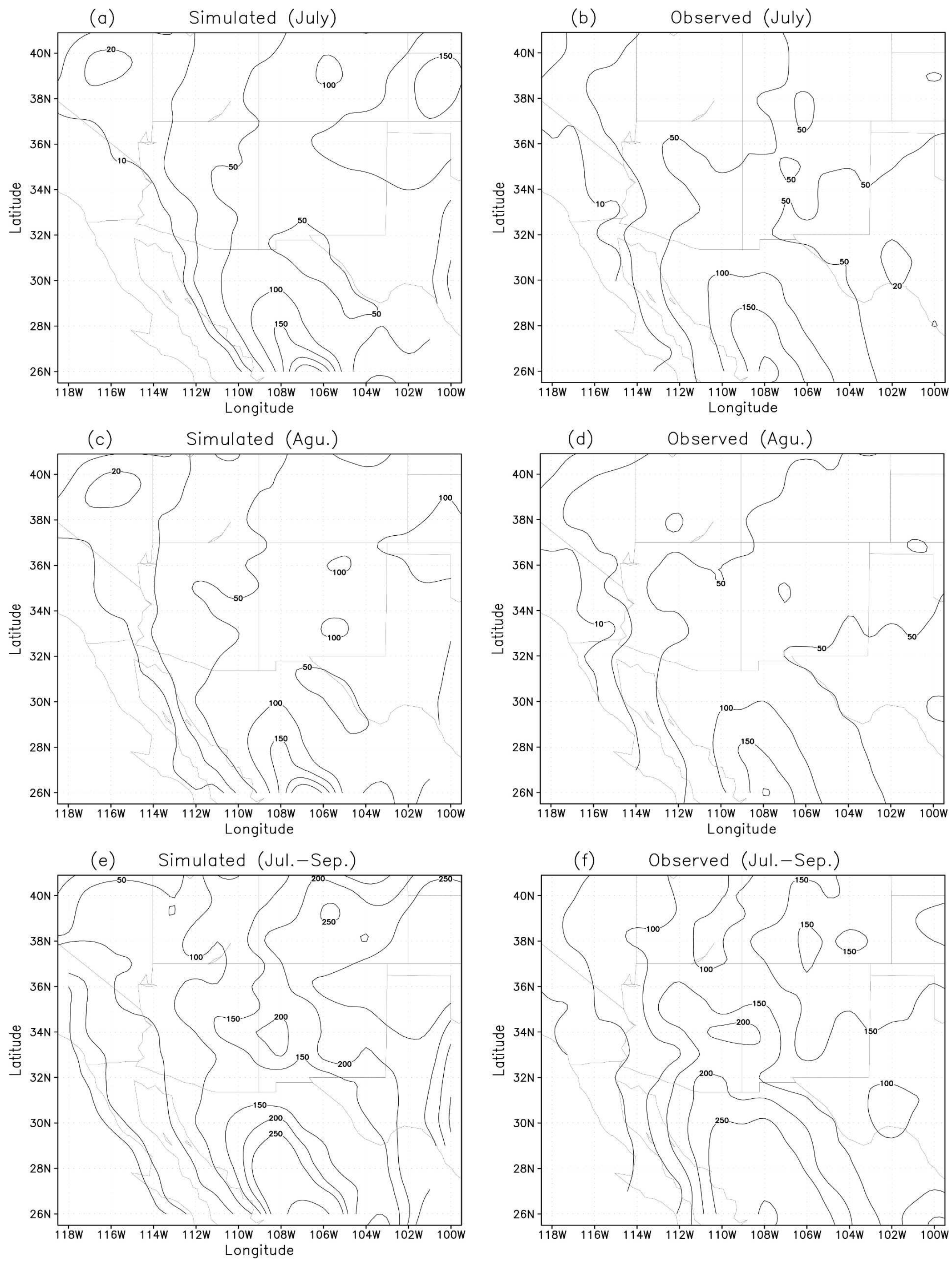

FIG. 2. (left) Simulated and (right) observed precipitation: (a),(b) July; (c),(d) August; and (e),(f) average of July–September. Unit is mm, and counter intervals are 10, 20, 50, 100, 150, 200, 250, and 500 mm. For comparison purposes, modeled precipitation was aggregated to 1.0° × 1.0° resolution.

the recent regime, and the region of increased geopotential extended farther to the areas of the eastern subtropical North Pacific near the model's southwest boundary. A decrease in geopotential is shown in those oceanic areas in the model result, however. Although this discrepancy is present, the major model results are consistent with the observations, for example, the increase in geopotential height in the north-central and

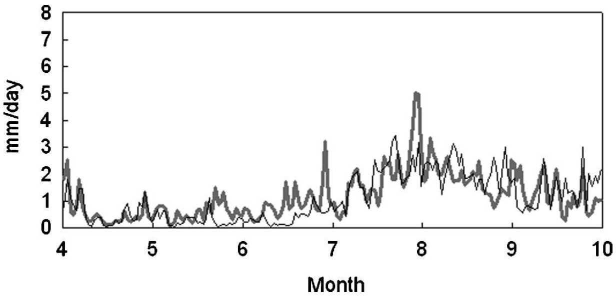

Fig. 3. Simulated (thick line) and observed (thin line) variations of 14-yr averaged precipitation in the southwest United States (an area within 32.0°–36.0°N and 107.5°–112.5°W).

western United States and the eastward shift of the trough to the eastern subtropical North Pacific off the west coast of the United States and Mexico (Figs. 5c–f).

The changes in geopotential heights over the central and western United States indicate an enhanced anticyclonic circulation in the recent regime. Because of weaker baroclinicity in enhanced anticyclonic regions, the geopotential changes also suggest weakened baroclinicity and storm activity in central and western United States. This speculation is supported by both the model results and observations in Fig. 7, which shows that the storm activity intensity, defined by the 300-hPa meridional wind variance (representing north–south eddy exchange) and calculated from the 24-h difference of meridional winds, STK $= \overline{(\upsilon_{t+24\mathrm{hr}} - \upsilon_t)^2}$ (Harnik and Chang 2003), weakened considerably in the central and western United States in accordance with rising geopotential height in the recent regime (areas of dashed lines in Fig. 7).

These changes in atmospheric geopotential and storm activity intensity between the two regimes concurred with weakened land memory effect in the recent regime. The higher pressure and weaker meridional eddy exchange of energy and momentum in the regional circulation of the western United States in the recent regime presumably reduced interactions between the northwest and the southwest United States. The weakened meridional exchange could have limited the influence of the local circulation anomalies in the northwest United States, for example, resulting from antecedent winter precipitation or snow cover anomalies and the subsequent spring season land surface water and energy flux anomalies, on the circulation and rainfall in the southwest United States. The limited exchanges of momentum and energy between the north and south would weaken the land memory effect.

The relationship between the increased geopotential heights–weakened storm activity in the western United States and weakened land memory effect in the recent regime also is supported by the simulated relationships between southwest U.S. July–September rainfall and 500-hPa height anomaly. As shown in Fig. 8a, July–September rainfall anomalies in the southwest United States have a strong association with geopotential height anomalies in the northwest (also extending to north-central) United States in 1982–88. This association disappeared in the recent regime after 1990 (Fig. 8b), as the land memory effect diminished. In this regime, rainfall in the southwest United States has been associated with negative geopotential anomalies over the southwest United States and west Mexico. This dramatic change, along with a similar change in the relationship between the July–September rainfall in the southwest United States and April–June geopotential height anomalies in the northwest United States in the simulations (figure not shown), is consistent with observations shown in previous studies (e.g., see Fig. 5c in Hu and Feng 2004a).

We now examine the circulation changes, focusing on low-level jets into the southwest United States during the two different regimes. We will examine how the low-level jet flows and moisture transport that contribute to the rainfall may be different between the regimes and how they may have been developed within the previously described larger-scale circulation anomalies.

c. *Different low-level circulations between regimes*

Low-level circulation changes between the regimes were examined using comparisons of composites of conditions for wet and dry monsoon periods during the same regime, and from comparisons between the differences in the two regimes. The former should help reveal the major circulation components and patterns that contributed to the monsoon rainfall anomalies and variations during a regime and the latter would uncover the differences in the circulation patterns that contributed to monsoon rainfall anomalies between the different regimes.

Figure 9 shows composites of simulated 500-hPa geopotential, wind, and vertically integrated moisture flux anomalies for wet and dry monsoon periods during the 1982–88 regime, and Fig. 10 shows similar anomalies for the more recent 1995–2001 regime. These composites were based on wet (dry) days in the southwest United States during the monsoon season (JAS). The wet (dry) days were defined as 20% of the wettest (driest), based on the rank of averaged daily precipitation over the southwest United States during the monsoon season in each regime. The anomalies in geopotential heights, wind, and moisture flux, relative to their daily mean in each regime, were determined for these wet and dry days. In Figs. 9c and 10c, the shaded areas indicate the

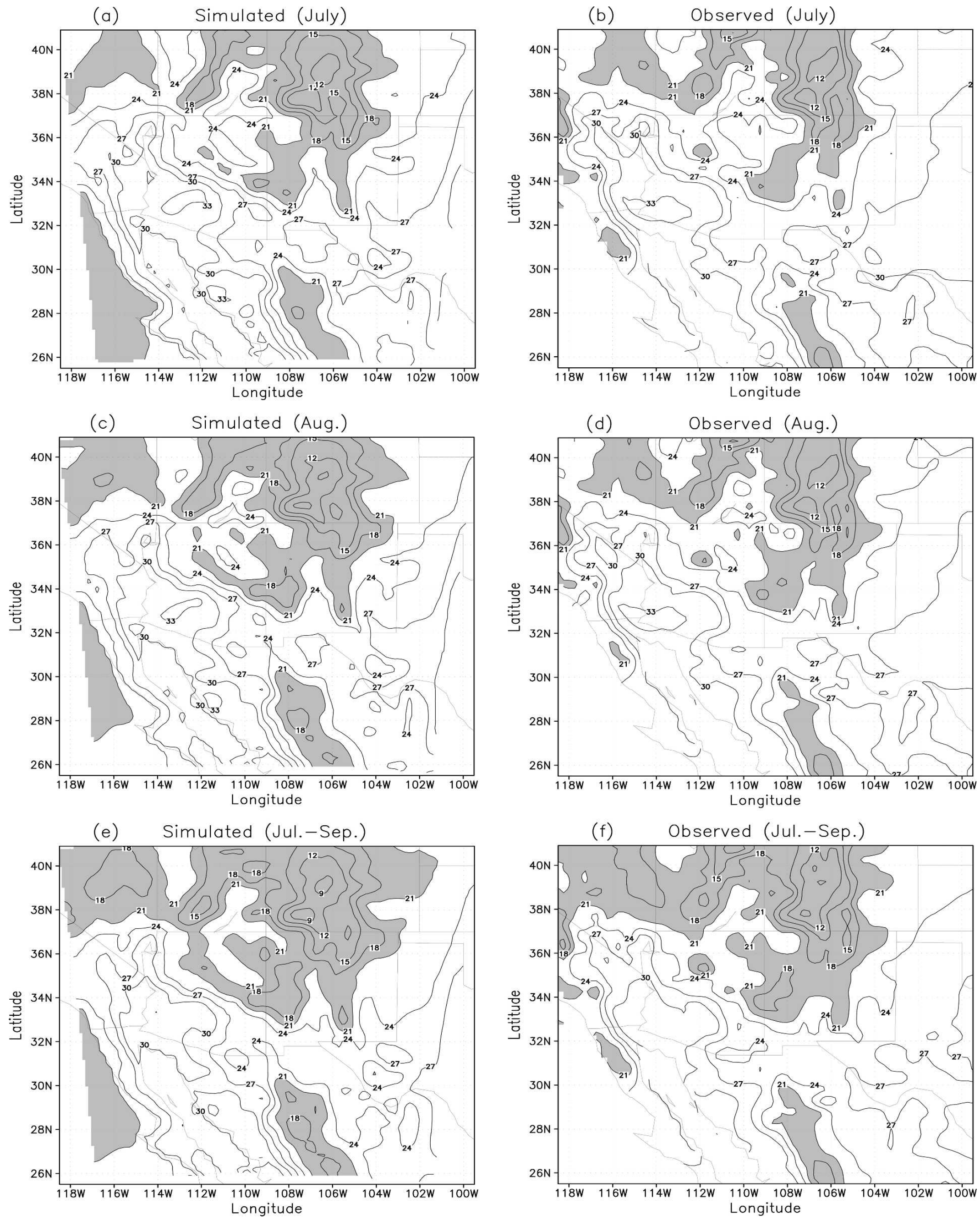

FIG. 4. As in Fig. 2, but for surface air temperature. Unit is °C; shading areas have temperatures cooler than 21°C; no observations of surface air temperature over the oceans in the southwest of the domain.

largest changes in geopotential and the arrows show the differences in vertically integrated surface–700-hPa moisture fluxes between wet and dry monsoon days/periods in different regimes.

In 1982–88 (Fig. 9), large changes in geopotential heights over the north-central United States occurred between wet and dry monsoon periods in the Southwest. Positive geopotential anomalies corresponded to wet condition (Fig. 9a), and negative anomalies to dry periods (Fig. 9b). In accordance with these geopotential changes, reversed flow anomalies occurred over the south and southwest United States: strong anomalous easterlies persisted over the southwest United States during the wet periods, and westerly anomalies pre-

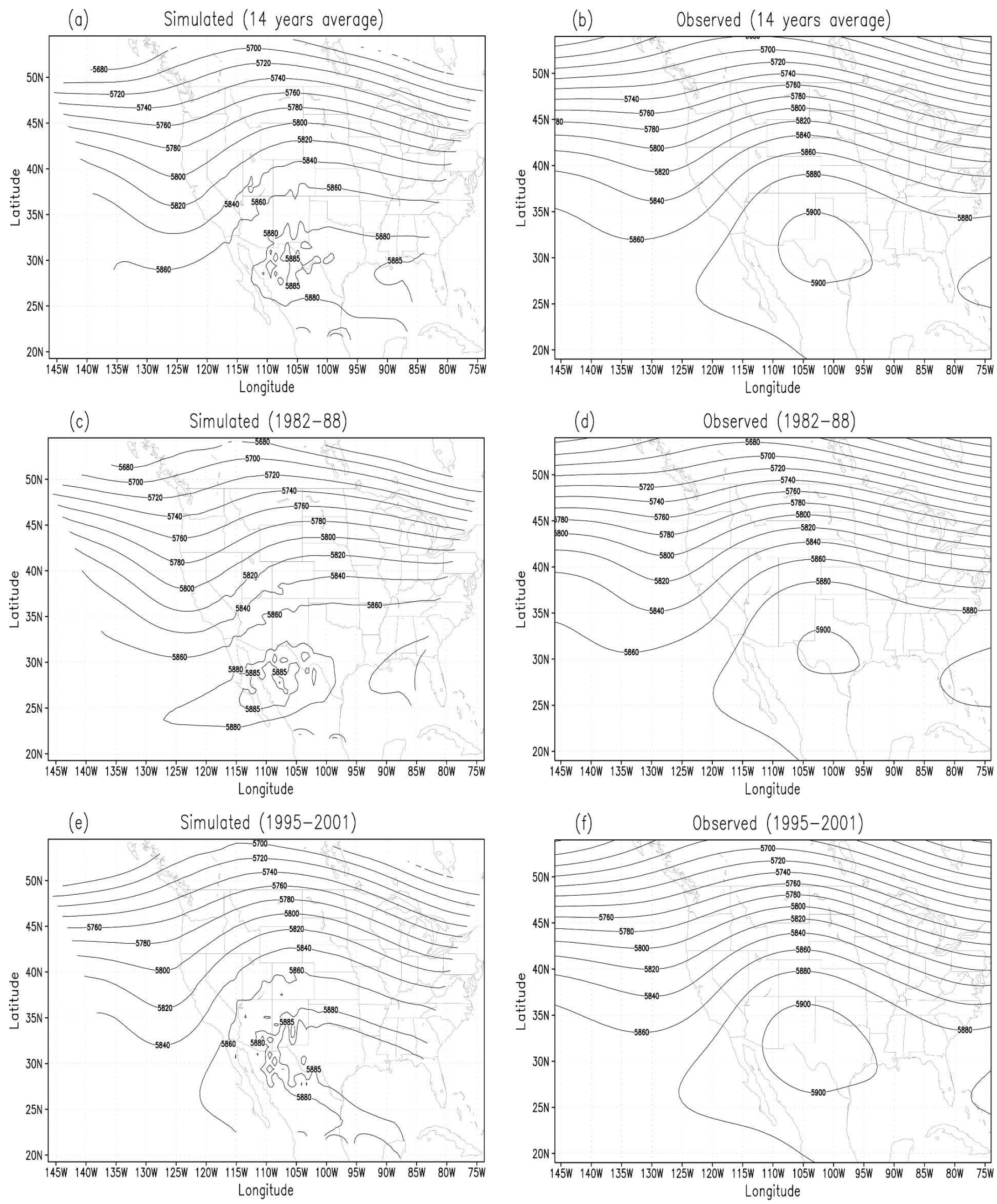

FIG. 5. (left) Simulated and (right) observed 500-hPa geopotential height: average (a),(b) of the 14 warm seasons, (c),(d) of the early regime (1982–88), and (e),(f) of the more recent regime (1995–2001). Units are $m^2\ s^{-2}$.

vailed during the dry periods. These westerly anomalies were unfavorable for rain development because of the cold SST off the West Coast of North America and relatively dry air in the subtropical high over the eastern North Pacific. Conversely, enhanced easterly and southeasterly anomalies over the southwest United States could have enhanced transport of moisture from the warm and moist east into the region, favoring more rainfall.

In contrast to these composites of circulation anomalies in the wet and dry periods for the early regime, the composites for the recent regime shown in Fig. 10 revealed dramatic differences. First, the geopotential anomaly center in the north-central United States in the previous regime (Fig. 9) weakened and "squashed" to the west and southeast. The center of the anomalies in the 500-hPa geopotential field was now in the southwest United States and northwest Mexico. Second, dur-

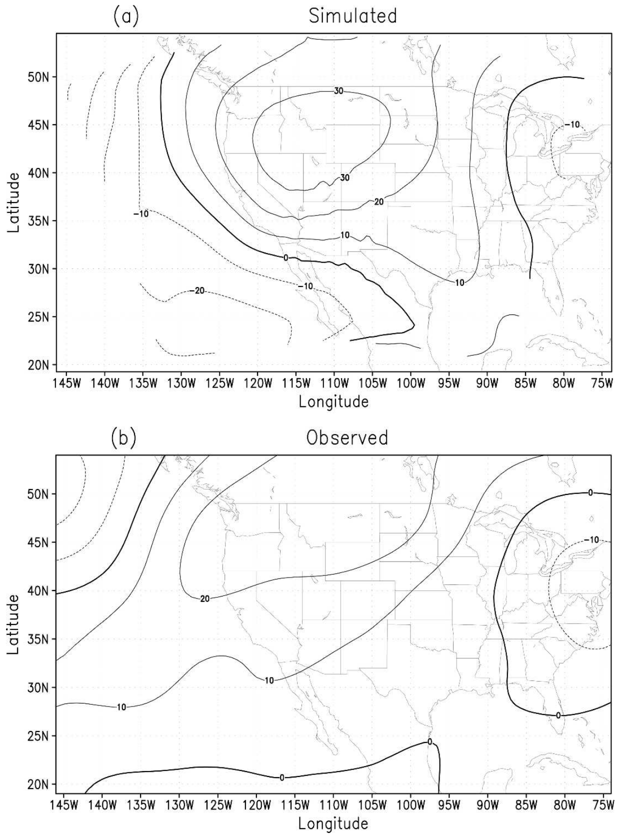

FIG. 6. (a) Simulated and (b) observed differences of 500-hPa geopotential height between the two different regimes (1995–2001 minus 1982–88). Units are $m^2 s^{-2}$.

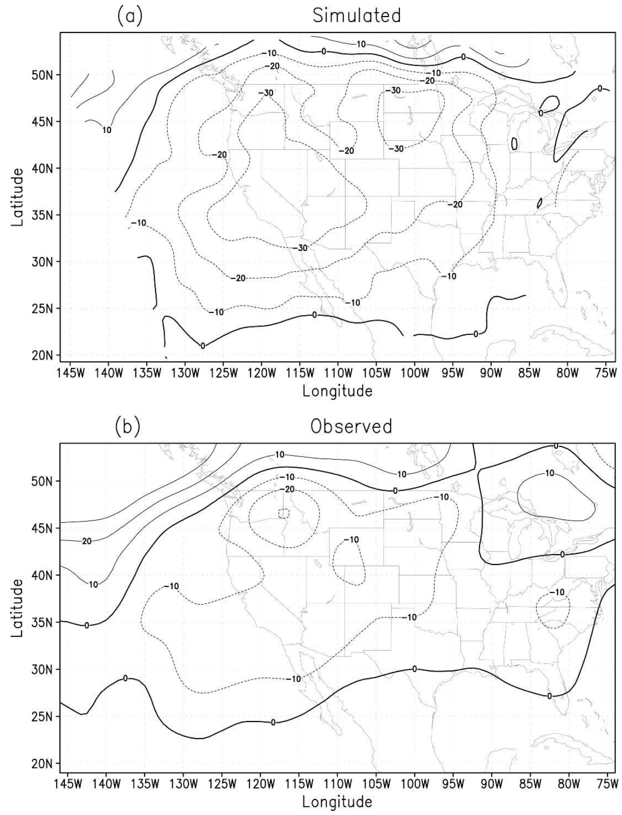

FIG. 7. As in Fig. 6, but for differences of 300-hPa storm-track anomalies. Units are $m^2 s^{-2}$, and negatives are shown in dashed lines. For clarity, contours ≤ -40 and ≥ 40 were omitted.

ing wet periods, the recent regime had expanded and enhanced negative anomalies of geopotential over the southwest United States and northwest Mexico. During dry periods larger positive geopotential anomalies occurred over the western United States and the eastern North Pacific.

Consistent with these 500-hPa geopotential changes in the recent regime, the circulation showed strong cyclonic anomalies in the southwest United States and west Mexico in the wet periods (Fig. 10a). Similar changes also occurred in the 700-hPa geopotential and wind anomalies. These circulation anomalies demonstrate an enhanced role of southerly flow from the Gulf of California in the recent regime, in contrast to the strong easterly and southeasterly flow anomalies, which played a dominant role for moisture transport and the monsoon rainfall variations during the earlier regime.

The vertically integrated moisture flux anomalies into the southwest United States also suggest different primary moisture sources of monsoon rainfall between the regimes (contrast the arrows in Figs. 9c and 10c). In the earlier regime, enhanced easterly flow anomalies transported moisture from the south-central and southeastern United States to the Southwest and corresponded to wet monsoons. When the moisture flows weakened/reversed dry monsoon occurred. In contrast, little change occurred between the wet and dry monsoons in southerly moisture transport from the Gulf of California and west Mexico into the southwest United States, indicating a relatively trivial role of the southerly moisture transport in the monsoon rainfall variations in the earlier regime.

During the recent regime, the vertically integrated moisture fluxes indicated that the primary moisture transport to the southwest United States was by the anomalous southerly and southwesterly flows from the Gulf of California, and oceanic regions farther south and southwest (Fig. 10c). When this moisture flux strengthened (weakened), the southwest United States experienced wet (dry) monsoons. While the southerly moisture flux from the Gulf of California dominated in the recent regime, low-level flows from the east were less important, suggesting moisture transports from the east and southeast became secondary to monsoon rainfall and variation.

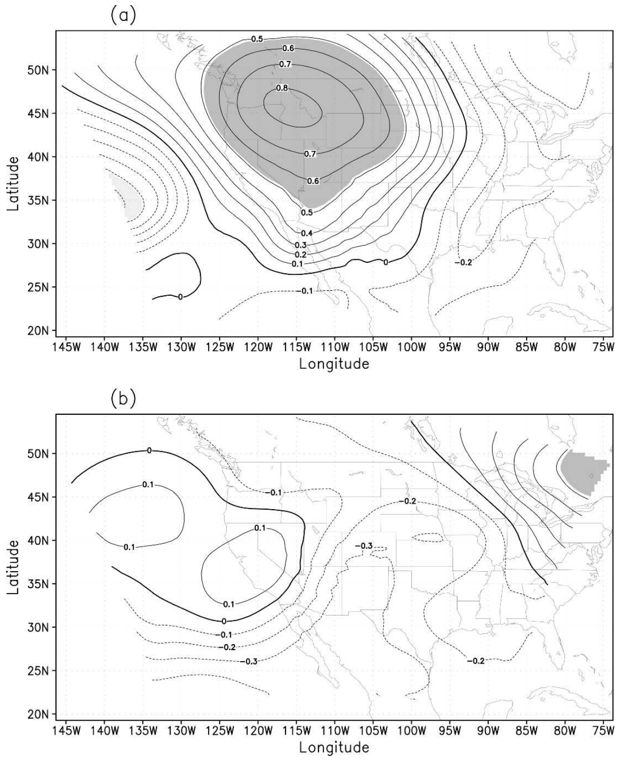

FIG. 8. Correlations of modeled July–September total rainfall in the southwest United States vs 500-hPa geopotential height for (a) 1982–88 and (b) 1995–2001. Shadings indicate statistically significant correlation at 95% confidence level. The correlation shown in this figure was calculated using simulated monthly rainfall and monthly geopotential height during the monsoon season (July–September). The total sample number used in the calculation in each epoch is 21 (3 months each year for 7 yr).

4. Discussions

Our major result is that alternations in anomalous moisture transport into the southwest United States, as part of large-scale circulation variations between the regimes, provides a means by which land memory effect and the North Pacific SST anomalies could have alternations in their way to impact rainfall in the southwest United States in the different regimes. This also indicates that different circulations persisted over the west United States and east North Pacific in those different regimes. In the earlier regime, the averaged geopotential heights were lower and the storm activity was more intense over the central and western United States. Strong exchanges of energy and momentum between the northwest and the southwest United States by the eddies could have helped engage interactions of regional circulations in the western United States. The large-scale circulation manifested by these features may have facilitated the land memory effect. Although the details of what physical processes may have been involved remains unclear, a qualitative understanding can be obtained from examining the circulation anomalies in Figs. 9 and 10. The anomalies of atmospheric circulation over the western North America and the eastern North Pacific had an anomaly centered over the central and western United States and south-central Canada (Fig. 9). These geopotential height anomalies affected the circulation in the southwest United States and its rainfall variation. Positive geopotential anomalies corresponded to stronger easterly flows and associated low-level moisture transport from the eastern and southeastern United States to the Southwest (Figs. 9a,c). These anomalies and resultant moisture transports yielded positive rainfall anomalies for the Southwest. Reversed anomalies of geopotential in the center resulted in anomalous westerly flows and drier conditions for the Southwest. Thus, changes of these geopotential and wind anomalies are responsible for both intraseasonal and interannual variations in monsoon rainfall in the southwest United States.

The geographical location of the anomaly center indicates that the geopotential anomalies may have been considerably influenced by the land surface and atmospheric processes in the northwest United States. As discussed in Hu and Feng (2004a), "a persistent negative anomaly of the soil enthalpy in the northwest United States is related to negative anomalies of the surface and lower-tropospheric temperatures." Positive anomalies of the surface and lower-troposphere temperature correspond to positive anomalies of soil enthalpy. These different temperatures in the northwest United States, presumably arising from differences in antecedent precipitation and snow cover anomalies and the resulting soil enthalpy anomalies (land memory), influence the geopotential field in the northwest and north-central United States and south-central Canada, and contribute to the geopotential height variations at the anomaly center downstream in the U.S. northern Great Plains and south-central Canada (see Fig. 9). Through the associated circulation anomalies previously described, these antecedent precipitation and snow cover anomalies in the northwest United States could have indirectly influenced the summer monsoon rainfall in the Southwest.

In the recent regime, the geopotential anomalies over the north-central United States and south-central Canada were "squashed." Instead, a major anomaly center appeared over the southwest United States and adjacent oceans to the west and southwest. These negative geopotential anomalies corresponded to strong low-level southerly and southwesterly flows and associated moisture transports from the Gulf of California into the Southwest, causing more rainfall. Positive geo-

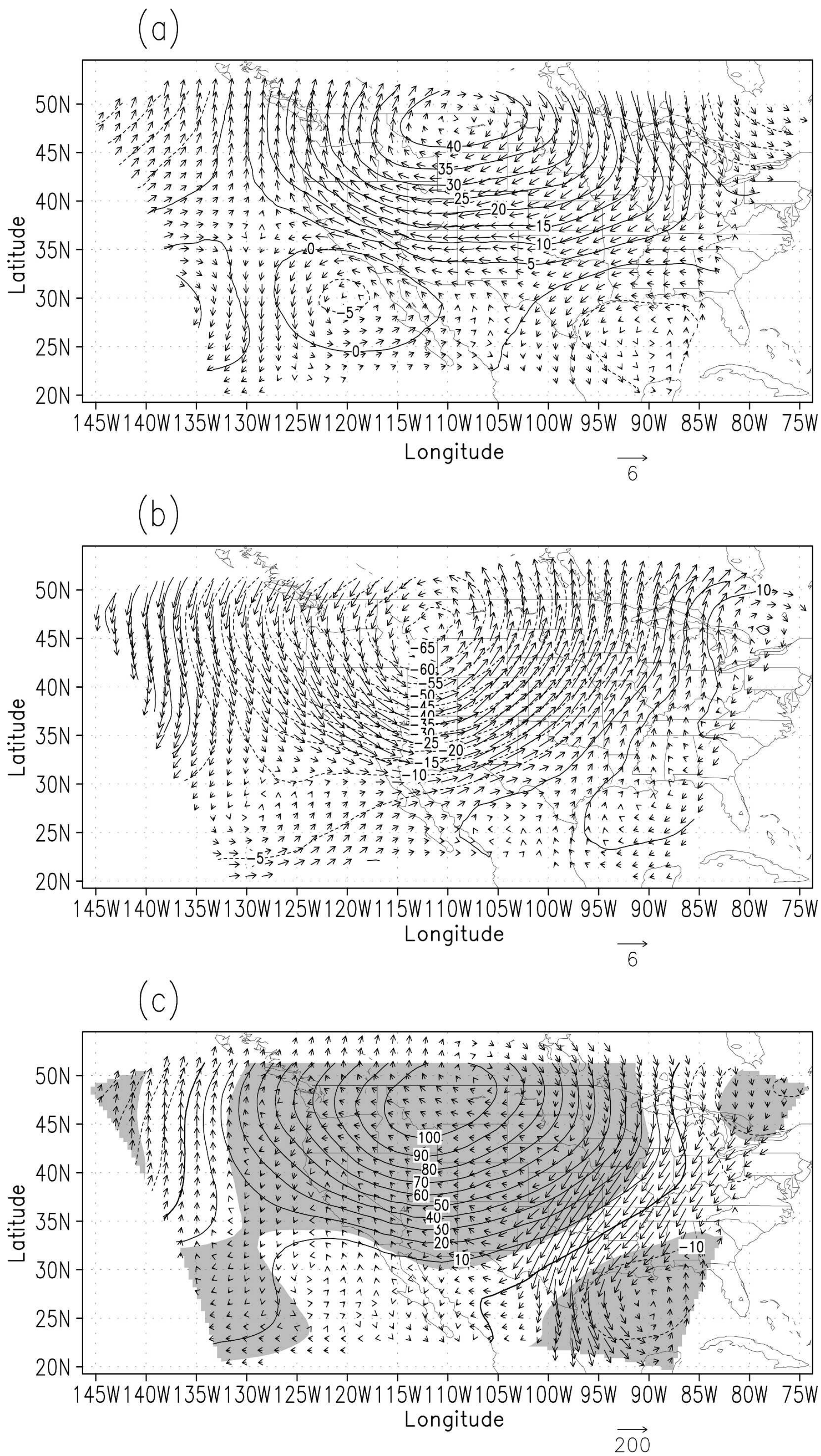

FIG. 9. (a), (b) Anomalies of 500-hPa geopotential height (contours, units are $m^2\ s^{-2}$) and wind (arrows, units are $m\ s^{-1}$) for wet and dry monsoon periods, respectively, in 1982–88. The scale for wind anomaly is shown in the lower-right corner under each plot. (c) Contours show difference of the geopotential height anomalies between (a) and (b), and arrows show difference of the surface–700-hPa moisture flux (units are $kg\ m^{-1}\ s^{-1}$) between wet and dry monsoon periods. Shadings indicate statistically significant difference at 95% confidence level.

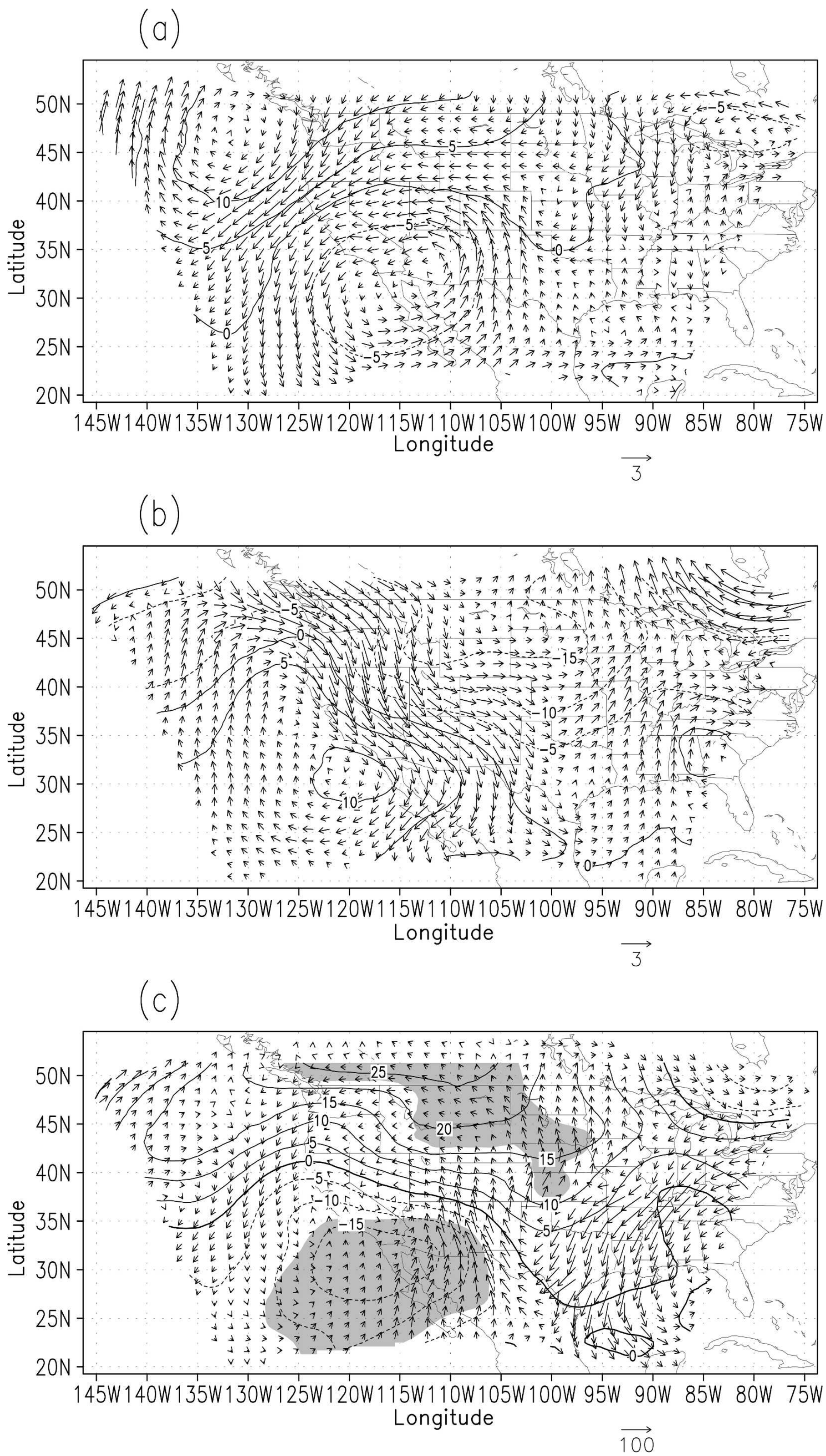

FIG. 10. As in Fig. 9, but for 1995–2001.

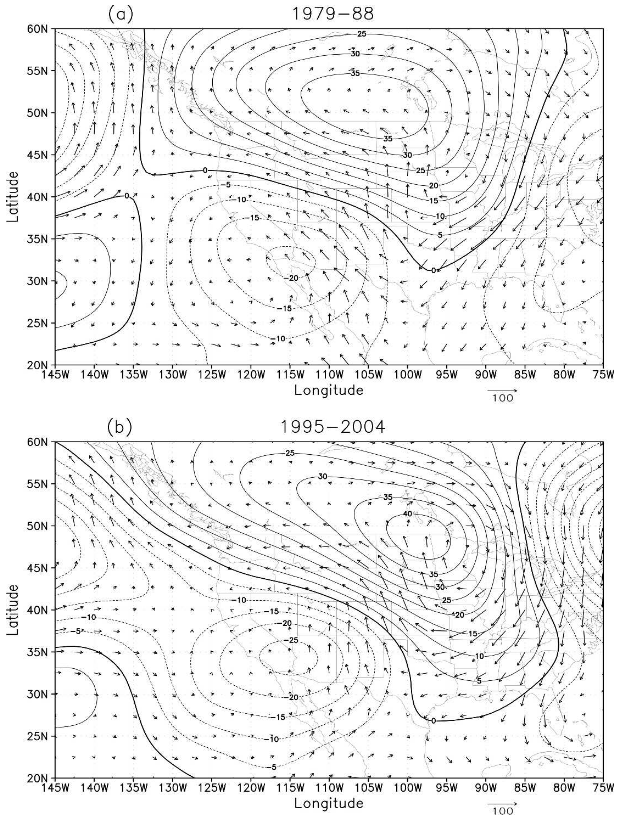

FIG. 11. Observed differences of 500-hPa geopotential height (contours, units are $m^2\ s^{-2}$) and surface–700-hPa moisture flux (arrows, units are $kg\ m^{-1}\ s^{-1}$) between wet and dry monsoon periods (wet minus dry) for (a) 1979–88 and (b) 1995–2004.

potential anomalies resulted in reversed flow anomalies and drier conditions. Because these circulation and moisture transport anomalies are more directly affected by temperature anomalies in the upstream east North Pacific, the North Pacific SST anomalies could have played an important role in the monsoon rainfall variations in the southwest United States in the recent regime.

These changes in regional circulation and moisture transport during the different regimes described in the model results also are observed, albeit the observed differences are not as dramatic as in the model results. The observed counterparts of Figs. 9c and 10c are shown in Figs. 11a,b, respectively. Note that because of the subtle differences in the observed wind between the regimes, we used more years in each regime in making Fig. 11; years 1979–88 were used to make Fig. 11a and years 1995–2004 for Fig. 11b. In Fig. 11a, the center of geopotential anomaly is shown over the north-central United States and south-central Canada, similar to the model result. Negative geopotential height anomalies enhance the easterly flows and moisture transports from the eastern and southeastern United States into the Southwest and correspond to wet monsoons. Positive geopotential height anomalies reverse the wind and moisture transport anomalies and favor drier monsoons. These variations are similar to that shown in Fig. 9c from the model, albeit the model results show stronger zonal flows than the observed.

In Fig. 11b (for the recent regime), the observed flow anomaly in the southwest United States show strong southerlies and northward transport of moisture in Arizona and New Mexico, also similar to the model result in Fig. 10c. In the north, the geopotential anomaly center in the north-central United States and south-central Canada in the earlier regime shifted to the east and changed its orientation to be more along the north–south direction. In the west fringe of this anomaly center, strong meridional flow anomalies in the central and western United States helped establish strong meridional moisture transport into the Arizona–New Mexico region. Moisture transport anomalies from southerlies and southwesterlies from the Gulf of California corresponded to wet conditions, and reversed flow anomalies were associated with drier conditions in the Southwest. Although these geopotential and related flow anomaly patterns and their changes from the earlier regime are not as dramatic as those in the model (Figs. 9c and 10c; suggesting the model has exaggerated to some extent the circulation differences between the regimes), they support the model result that different circulation anomalies in the western North America and the eastern North Pacific existed during those different regimes. These different circulation anomalies may have provided a means by which land memory effect and the North Pacific SST anomalies and associated different low-level moisture transport alternated in their way to impact rainfall and its variations in the southwest United States.

5. Summary and concluding remarks

Numerical simulations of warm season rainfall in the southwest United States from the MM5 illustrate different atmospheric circulation anomalies, for example, geopotential heights, eddy exchange, and storm activity, in the western United States and eastern North Pacific. The anomalous circulation pattern in the earlier regime (1961–90) demonstrates a sole strong geopotential anomaly center in the north-central United States and south-central Canada. Surrounding this prominent anomaly center the wind field shows strong zonal flow anomalies in the south-central and southwestern United States. During the easterly wind anomalies, moisture transport from the eastern and southeastern

United States to the Southwest corresponds to above-normal precipitation during the monsoon. In the reversed anomalies, below-normal monsoon rainfall is observed. As we postulated, the strong geopotential anomaly center in this regime could have been influenced by the anomalies of the surface fluxes in the upstream northwestern United States, although details of how the surface fluxes are influencing the geopotential anomaly center in this regime remains to be examined. This geopotential anomaly patterns could have favored the land memory effect and connected it with the southwest U.S. monsoon rainfall through the regional wind and moisture transport anomalies from the east and southeast to the Southwest.

In the recent regime (from 1990 on), the geopotential anomaly center in the north-central United States and south-central Canada is replaced by broader and much weaker anomalies from the central to the western midlatitude North America. A strong geopotential anomaly center is established in the southwestern United States and eastern North Pacific in 30°–35°N. To its east is an opposite geopotential anomaly center. Between these two major centers of geopotential anomaly are strong meridional wind anomalies, with suppressed zonal wind anomalies. This different configuration of geopotential and associated wind anomalies in this regime bring different processes to the monsoon rainfall variations in the Southwest. Rainfall was enhanced in the seasons with strong anomalous southerly and southwesterly flows from the Gulf of California but was reduced substantially when the flow anomaly was primarily northerlies. It is noticed that the zonal flow anomalies in the south-central and southwest United States played a trivial role in this regime. These results indicate that persistent circulation anomalies in the different regimes in the central and western United States and the eastern North Pacific affected the low-level moisture transport into the southwest United States and its monsoon rainfall in those regimes.

These model-suggested decadal-scale variations of the circulation anomalies and associated primary moisture sources influencing the monsoon rainfall variations also are shown in the observations, although comparisons indicate that the model results exaggerated the contrast of the circulation anomalies in the different regimes. While further studies are required to examine the details for the causes of the differences between the model and the observation some additional evidence seems supporting the model results. For example, Douglas et al. (1993) observed strong easterly and southeasterly flows from east (the region connected to the Gulf of Mexico) to the southwest United States and showed their influence on the southwest U.S. rainfall in the years of 1979–89, that is, prior to 1990. They proposed easterly and southeasterly moisture transport as a key moisture source for warm season rainfall and its variation in the southwest United States during those years. More recently, several studies focused on the period after 1990 (e.g., Douglas 1995; Stensrud et al. 1997; Adams and Comrie 1997; Berbery 2001; Anderson et al. 2002; Mo and Juang 2003) have reported increased southerly and southwesterly moisture fluxes from the Gulf of California and their influence on monsoon rainfall variations in the southwest United States.

Additional studies will be necessary to identify and understand the physical processes that amplify the influence of the low-level flows from the different origins and develop rainfall in the southwest United States in the different anomalous circulation environments. Gaining these understandings will lead to improvement in predictions of monsoon rainfall in the southwest United States on seasonal, interannual, and potentially even decadal time scales.

Acknowledgments. We thank Dr. Robert Oglesby and three anonymous reviewers for their valuable suggestions and comments leading to improvements of this manuscript, which has been supported by the USDA Cooperative Research Project NEB-40-040.

REFERENCES

Adams, D. K., and A. C. Comrie, 1997: The North American monsoon. *Bull. Amer. Meteor. Soc.,* **78,** 2197–2213.

Anderson, B. T., J. O. Roads, and S. C. Chen, 2000: Large scale forcing of summertime monsoon surges over the Gulf of California and southwestern United States. *J. Geophys. Res.,* **105,** 24 455–24 467.

Berbery, E. H., 2001: Mesoscale moisture analysis of the North American monsoon. *J. Climate,* **14,** 121–137.

Carleton, A. M., D. A. Carpenter, and P. J. Weser, 1990: Mechanisms of interannual variability of the southwest United States summer rainfall maximum. *J. Climate,* **3,** 999–1015.

Castro, C. L., T. B. McKee, and R. A. Pielke Sr., 2001: The relationship of the North American monsoon to tropical and North Pacific sea surface temperatures as revealed by observational analyses. *J. Climate,* **14,** 4449–4473.

Chen, F., and Coauthors, 1996: Modeling of land surface evaporation by four schemes and comparison with FIFE observations. *J. Geophys. Res.,* **101D,** 7251–7268.

Douglas, M. W., 1995: The summertime low level jet over the Gulf of California. *Mon. Wea. Rev.,* **123,** 2334–2347.

——, R. Maddox, K. Howard, and S. Reyes, 1993: The Mexican monsoon. *J. Climate,* **6,** 1665–1667.

Gochis, D. J., W. J. Shuttleworth, and Z. L. Yang, 2003: Hydrometeorological response of modeled North American monsoon to convective parameterization. *J. Hydrometeor.,* **4,** 235–250.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994: A description of the fifth generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-3801+STR, 138 pp.

Gutzler, D. S., 2000: Covariability of spring snowpack and summer rainfall across the southwest United States. *J. Climate,* **13,** 4018–4027.

——, and J. W. Preston, 1997: Evidence for a relationship between spring snow cover in North America and summer rainfall in New Mexico. *Geophys. Res. Lett.,* **24,** 2207–2210.

——, and Coauthors, 2005: The North American Monsoon Model Assessment Project: Integrating numerical modeling into a field-based process study. *Bull. Amer. Meteor. Soc.,* **86,** 1423–1429.

Hales, J. E., 1972: Surges of maritime tropical air northward over the Gulf of California. *Mon. Wea. Rev.,* **100,** 298–306.

Harnik, N., and E. K. M. Chang, 2003: Storm track variations as seen in radiosonde observations and reanalysis data. *J. Climate,* **16,** 480–495.

Higgins, R. W., and W. Shi, 2000: Dominant factors responsible for interannual variability of the summer monsoon in the southwestern United States. *J. Climate,* **13,** 759–775.

——, ——, E. Yarosh, and R. Joyce, 2000: *Improved United States Precipitation Quality Control System and Analysis.* NCEP/Climate Prediction Center Atlas 7, 40 pp.

Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium range forecast model. *Mon. Wea. Rev.,* **124,** 2322–2339.

Hu, Q., and S. Feng, 2002: Interannual rainfall variations in the North American summer monsoon region: 1900–98. *J. Climate,* **15,** 1189–1202.

——, and ——, 2004a: A role of the soil enthalpy in land memory. *J. Climate,* **17,** 3632–3642.

——, and ——, 2004b: Why has the land memory changed? *J. Climate,* **17,** 3236–3243.

Kain, J. S., and M. Fritsch, 1990: A one-dimensional entraining/detraining plume model and its application in convective parameterization. *J. Atmos. Sci.,* **47,** 2784–2802.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Mo, K. C., and H. M. H. Juang, 2003: Influence of sea surface temperature anomalies in the Gulf of California on North American monsoon rainfall. *J. Geophys. Res.,* **108,** 4112, doi:10.1029/2002JD002403.

New, M., M. Hulme, and P. Jones, 2000: Representing twentieth-century space–time climate variability. Part II: Development of 1901–96 monthly grids of terrestrial surface climate. *J. Climate,* **13,** 2217–2238.

Rasmusson, E. M., 1967: Atmospheric water vapor transport and the water balance of North America: Part I. Characteristics of the water vapor flux field. *Mon. Wea. Rev.,* **95,** 403–426.

Reynolds, R. W., and T. M. Smith, 1994: Improved global sea surface temperature analyses. *J. Climate,* **7,** 929–948.

Ropelewski, C. F., D. S. Gutzler, R. W. Higgins, and C. R. Mechoso, 2005: The North American monsoon system. The Global Monsoon System: Research and Forecast, World Meteorological Organization Tech. Doc. 1266, 207–218.

Schmitz, J. T., and S. L. Mullen, 1996: Water vapor transport associated with the summertime North American monsoon as depicted by ECMWF analyses. *J. Climate,* **9,** 1621–1634.

Stensrud, D. J., R. L. Gall, and M. K. Nordquist, 1997: Surge over the Gulf of California during the Mexico monsoon. *Mon. Wea. Rev.,* **125,** 417–437.